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13. ABSTRACT (Maximum 200 words)  A research program was carried out to investigate turbulent mixing in stably stratified shear flows with the hope of gaining an improved understanding of stably stratified nocturnal boundary layers. The program was mainly laboratory experimental, supplemented by theoretical and numerical developments. The flow configuration consisted of a three-layer system, with upper turbulent layer driven over the lower stratified, quiescent, layer while an intermediate (inversion) layer sandwiched between these two layers. The studies included the nature of instabilities, intermittent generation of turbulence, sustenance and decay of turbulence under varying background conditions (essentially determined by the Richardson number) and ensuing turbulent mixing in the inversion layer. An unprecedented volume of laboratory data were gathered during the program, which enabled to delve into the mechanics and energetics of mixing in stable boundary layers. The laboratory results were compared with, and was used to gain insights on, field observations. Also, the parameterizations developed were compared with those currently used in numerical models. A meso-scale numerical model also was used to check the efficacy of some of the laboratory-based parameterizations.				
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**TURBULENCE AND MIXING IN STRATIFIED SHEAR FLOWS**

**FINAL TECHNICAL REPORT**

**by**

**H.J.S. Fernando and D.L. Boyer**

**U.S. ARMY RESEARCH OFFICE**

**GRANT NUMBER; DAAH-04-95-1-0132**

**ARIZONA STATE UNIVERSITY**

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## **INTRODUCTION:**

The aim of the research program being reported was to understand, using laboratory experiments, numerical modeling and theoretical analysis, the processes occurring in the nocturnal atmospheric boundary layer. Particular attention was paid to the generation, maintenance and decay of turbulence in such boundary layers. Aspects of stratified shear layers investigated were: (i) the generation of turbulence and its relation to the stability of the shear layer, specified by the Richardson number, (ii) the mechanisms of turbulence generation, (iii) the energetics of the shear layer, (iv) processes occurring at different scales and their implications in local measurements, and (iv) the parameterization of stratified turbulence in turbulent inversion layers.

During the contract period, the Principal Investigators H.J.S. Fernando and D.L. Boyer, graduate students Eric Strang and John Rotter, post-doctoral fellow Andrey Grachev and visiting scientists Professors Eliezer Kit (Tel Aviv University) and J.C.R. Hunt (U.K. Meteorological Office) worked on different facets of the nocturnal boundary layer turbulence problem and published their results in various journals and conference proceedings. Given that the results are (or will be) available in the open literature, only a summary of the major findings are listed below and the resulting publications can be found at the end of this report.

## **METHODOLOGY:**

The major part of the research was laboratory experimental, conducted by generating stratified shear layers in water tanks. A series of experiments was performed in a recirculating (race-track shaped) water channel, whereby an upper turbulent layer was driven over a stagnant denser layer. The intermediate (inversion) layer developed between the two layers was strongly stratified and sheared, providing a suitable flow configuration for studies on stably stratified boundary layers. A uniquely designed disk pump was used to drive the flow and special precautionary measures were used to ensure one-dimensional growth of the upper turbulent layer, which ensured the generation of a

vertically sheared stable layer sandwiched between upper and lower layers. Detailed measurements using the laser-Doppler, hot film and particle-image velocimetry techniques as well as flow imaging using the laser-induced fluorescence (LIF) method were used for flow diagnostics. The data were used to identify primary mechanisms responsible for entrainment, to determine the morphological aspects of entrainment, to measure and parameterize the rate of entrainment, to assess the significance of internal wave radiation off the base of the upper mixed-layer into the stratified layer(s) and to evaluate the TKE balance at the shear layer. Because of the non-stationary nature of the experiments, the measurements were intricate and space-time scales of averaging needed to be selected with utmost care. The measurements included the production of turbulent kinetic energy, buoyancy flux, rate of dissipation, internal wave radiation, integral-scales of turbulence and the local Richardson number with a resolution of 2.5 mm (using a specially designed probe).

## RESULTS AND INFERENCES:

During the experiments, a well-defined stratified shear layer was found to develop between the upper turbulent layer (of depth  $D$  and velocity  $U$ ) and the stagnant, deep lower layer (which is either homogeneous or weakly linearly stratified with a buoyancy frequency  $N$ ). The problem was mainly determined by two dimensionless parameters, the bulk Richardson number  $Ri_B = \Delta b D / \Delta U^2$  and the frequency ratio  $f_N = ND / \Delta U$ , where the velocity and buoyancy jumps across the interface are  $\Delta U$  and  $\Delta b$ , respectively. It was shown that, when  $Ri_B > 1.5$ , the buoyancy effects play a governing role in the entrainment process, whence interfacial instabilities locally mix heavy and light fluids. Such local mixing facilitates the scour and transport of heavy fluid from the interfacial area to the upper layer by turbulent eddies. The nature of interfacial instabilities is governed by  $Ri_B$  or a related quantity, the mean local gradient Richardson number  $Ri_g = N_i^2 / (du/dz)^2$ ; here,  $N_i$  is the local buoyancy frequency within the shear layer and  $du/dz$  is the corresponding shear. When  $Ri_B < 5$  (or  $Ri_g < 1$ ), the interfacial mixing is dominated by Kelvin-

Helmholtz (K-H) instabilities. They appear as a train of billows and collectively break down to form a local region of intense turbulence [with thickness  $0.22(\Delta U^2/\Delta b)$ ], thus resulting in local thickening of the shear layer. This process temporarily reduces the interfacial local gradient Richardson number and prevents further K-H occurrences, until the interface sharpens again due to its erosion by the upper-layer eddies and reduces  $Ri_g$  below a critical value. The interfacial swelling (thickening) persists for a time dictated by the rates of local generation and removal of mixed fluid, and the two processes appear to be coadjutant (with a maximum mixing efficiency or a flux Richardson number of  $Ri_f = 0.15-0.4$ ) when  $Ri_g$  is at around the upper cut-off of the K-H regime ( $Ri_B = 3-5$ ). Because of the disparity between production and transport rates of locally mixed fluid, often there is a time-dependent "intermediate layer" above the permanent interfacial layer. This intermediate layer fades away with the transitioning of the K-H regime into a new regime at  $Ri_B \sim 5$ , wherein the interface is dominated by interfacial/Holmboe wave instabilities. In this new regime, the entrainment rates are much smaller and there is no evidence of interfacial swelling.

In the K-H regime, the swelling of the interface introduces its own forcing time scale, which excites and radiates internal waves in the lower layer if it is continuously stratified. Consequently, the amount of energy available for entrainment decreases and, depending on  $f_N$ , the entrainment velocities in the linearly stratified case can be substantially smaller than the two-layer case (up to 50%). In the interfacial/Holmboe wave breaking regime, internal wave radiation to the bottom layer is much smaller, as indicated by the weak difference in entrainment rates of the two-layer and linearly stratified cases. The effects of the internal wave radiation are also evident in the measurements of shear-layer thickness, distortions and buoyancy flux.

Overall, the results show that when  $Ri_B < 3$  the entrainment rate is limited by the rate of transport of locally mixed fluid away from the interface by the scouring action of mixed-layer eddies and at  $Ri_B > 5$  the rate-limiting process is the production of locally

mixed fluid by interfacial/Holmboe wave breaking. When  $Ri_B > 5$ , the shear layer shows an approximate balance between the production of turbulent kinetic energy, its dissipation and the buoyancy flux whereas at  $Ri_B < 5$  such a quasi-equilibrium state is achieved only in an approximate sense.

K-H billowing effectively rolls up the interface, and their subsequent collapse leads to fine-scale turbulence which mixes and thickens the interfacial layer, thus increasing the local  $Ri_g$  and preventing further K-H billowing temporarily. Thereafter, the density interface is re-thinned by turbulent eddies which advect by and scour the diluted interfacial fluid. During the thinning of the interface, the local  $Ri_g$  decreases, as a result of which K-H instabilities recur. In essence, the present work provides first evidence for the conjecture used in some numerical models that K-H instability reduces the energy requirements for the turbulence to lift interfacial fluid away and incorporate it into the mixed-layer.

The entrainment rate measurements showed some interesting trends with increasing  $Ri_B$ . The rate of penetration of the upper turbulent layer into the shear layer was found to decrease by more than a factor of two at  $Ri_g \sim 0.3$  (or  $Ri_B \sim 2.8$ ) and had decayed by almost an order of magnitude (factor of five) at  $Ri_g \sim 1.0$  or  $Ri_B \sim 5.0$ . In conclusion, for  $Ri_B < 5$ , entrainment is significant in the K-H regime, and the mixing efficiency peaks at the upper boundary of the K-H regime  $Ri_B \sim 3-5$ . The sharp reduction of the entrainment at  $Ri_B \sim 5$  (or  $Ri_g \sim 1$ ) could be attributed to the cessation of K-H activity. Thus, for modeling purposes  $Ri_g \sim 1$  can be construed as the upper bound of a regime where effective entrainment is taking place. Our results were also found to be consistent with available sparse oceanic and atmospheric data and, therefore, provide useful guidance for developing constraints on parameters used to develop practical mixed-layer models.

As mentioned, entrainment occurs due to local mixing at the interface and subsequent transport of this fluid into the mixed-layer by turbulent eddies. The relatively

high entrainment rates observed in the K-H regime,  $3 < Ri_B < 5$ , could be attributed to the enhanced vertical transport of locally mixed fluid by the eddies; in this  $Ri_B$  range, the time scale of the short-lived stratification of an intermediate layer produced by local mixing coincides with the frequency of turbulent eddies present at the interface; that is, the normalized frequency  $N_I \delta_{bh} / w_{rms}$  is of the order unity, where  $N_I$  is the buoyancy frequency of the shear layer,  $w_{rms}$  is the rms of vertical velocity fluctuations within this layer and  $\delta_{bh}$  is the billow height.

The measurements indicate that the presence of stratification in the deep stagnant layer can result in a significant reduction of the entrainment rate. In particular, this was observed to be most dramatic in the K-H regime,  $2 < Ri_g < 5$ . The measurements of the interfacial thickness, distortions and buoyancy flux supported this conclusion. In this regime, the rate of entrainment decreased by 50% when  $f_N \sim 4$ . Evidence showed that the radiating internal wave field is excited by K-H related interfacial swelling, which generates an interfacial perturbation with a wavelength of the order of the mixed-layer depth. It is speculated that the internal waves transport energy to the interior of the deep layer where it is dissipated by viscous effects associated with propagation and reflection. The measurements of the flux Richardson number or the mixing efficiency  $Ri_f$  indicate a peak efficiency for entrainment at  $Ri_B \sim 5$ , which is approximately 0.15 to 0.4. As stated, this occurs when the time scale of mixed-layer eddies in the vicinity of the interface is comparable to the time scale associated with the stratification developed due to local mixing at the interface by K-H billows. Evaluation of detailed interfacial energetics indicate that the turbulent shear production approximately balances the turbulent buoyancy flux and the rate of dissipation for the case of a two-layer stratification for  $Ri_B > 5$ , and hence for practical purposes the interface can be considered as in a quasi-equilibrium state.

Measurements performed vertically across the stratified shear layer were used to estimate the eddy diffusivities of density and momentum,  $K_\rho$  and  $K_m$ , respectively.



When properly scaled, comparisons of these values with those deduced by oceanic and atmospheric finestructure measurements and several expressions used for oceanic stratified shear layer parameterizations indicated a fair agreement. Laboratory data, however, were typically larger than upper bounds of these estimates. When mixing is active,  $Ri_B < 5$  (or  $Ri_g < 1$ ),  $K_p$  was found to be approximately equal to  $K_m$ ; this assumption is commonly used in numerical models at all  $Ri_B$ , although our data show that, at large  $Ri_B$ , the momentum transfer coefficients are higher than its buoyancy transfer counterpart.

Detailed studies carried to investigate the behavior of instantaneous local gradient Richardson number  $Ri_g(t)$  in the stratified shear layer. The two point laser-Doppler anemometer and conductivity probe assembly with a resolution of  $\Delta z = 0.27$  cm and two laser Doppler anemometers/conductivity probe assemblies were used for this purpose; in the latter case,  $Ri_g(t)$  was measured at lesser resolutions ( $\Delta z > 1.8$  cm). Although the mean background flow was quasi-steady,  $Ri_g(t)$  was highly time dependent due to the variable internal strain field of instabilities, waves and turbulence. When K-H instabilities were present, the time-averaged gradient Richardson number  $Ri_{gav}$  ( $\Delta z = 0.27$  cm) was approximately a constant, in the range 0.04-0.08, irrespective of  $Ri_B$ . When K-H instabilities were absent  $Ri_{gav}$  ( $\Delta z = 0.27$  cm) assumed larger values that are dependent on  $Ri_B$ .  $Ri_{gav}$  ( $\Delta z = 0.27$  cm) was always found to be dependent on  $\Delta z$  and  $Ri_B$ . It was argued that  $Ri_{gav}$  should be measured with a resolution better than the scale of density overturns to properly account for vertical small-scale processes of the stratified shear layer. The measurements are consistent with the notion that when  $Ri_B < 10$  or so, the energy supplied to a shear layer at large scales can be dissipated at smaller scales by the turbulence associated with the breakdown of K-H instabilities. These instabilities are characterized by the occurrence of a critical local  $Ri_{gav}$  measured at scales smaller than the overturning scale.



Attempts were also made to use laboratory-based mixing parameterizations for the purpose of fine tuning atmospheric numerical models. To this end, we used the HOTMAC mesoscale numerical model (developed at the Los Alamos National Laboratory) to predict the mesoscale meteorology in the El Paso complex terrain area; the sensitivity of this model to the mixing parameterizations employed was studied. The predictions were found to have a strong dependence on the parameterization employed.

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**INVENTIONS: NONE**